

Circular No. 50

1956

STATE OF ILLINOIS
WILLIAM G. STRATTON, *Governor*



Report on
Loss in Carrying Capacity
of Water Mains

by
T. E. LARSON

Issued by
DEPARTMENT OF REGISTRATION AND EDUCATION

VERA M. BINKS, *Director*
State Water Survey Division

A. M. BUSWELL, *Chief*
URBANA, ILLINOIS

(23210—8-56)



Report on Loss in Carrying Capacity of Water Mains

T. E. Larson

A paper presented on Jun. 15, 1955, at the Annual Conference, Chicago, Ill., by T. E. Larson, Head, Chemistry Subdiv., State Water Survey, Urbana, Ill. This report was prepared for AWWA Committee 2810 D—Effect of Purification Methods on Water Main Carrying Capacities, whose function is to advise, assist, and supplement the study being conducted on this subject by the Illinois Water Survey.

THE loss of main carrying capacity through corrosion and precipitation is a very serious problem. The replacement value of municipal distribution systems in the United States is estimated at approximately ten billion dollars. In many systems the carrying capacity has been reduced by more than 50 per cent. As the majority of mains in service are coal tar-coated cast iron, the present study is primarily concerned with this type. The investigation has been further limited, though only temporarily, to the mains of municipalities using Great Lakes waters, because: first, such untreated water is generally considered to be relatively noncorrosive; second, many cities use such water; and, third, unpublished reports and other data indicate an appreciable variety in the carrying-capacity losses experienced at various cities.

Because loss in carrying capacity is associated with the "roughness" of the interior of the pipe, it is important to define the different types of roughness that may develop:

1. The slime deposit or growth of bacteria, whether or not manganese or iron is present, generally occurs over the entire main surface. This condition is not known to exist when raw

or treated Great Lakes waters are used.

2. Deposition of silt from untreated water is not uncommon in old mains or those operating under conditions of low flow. Such depositions are known to be present even where water clarification has been practiced for over 20 years. In addition to sand, samples have been found to contain aluminosilicate clays and microorganisms. The effect of these deposits on carrying capacity is probably only slightly greater than calculations from the reduction of the pipe cross section would indicate.

3. Incrustation, or the formation of a crust over the metal surface, may be of various kinds, such as: [a] tuberculation in the form of nodules or spicules, resulting from localized corrosion; or [b] afterprecipitation or uniform deposition (not always a hard crust) of insoluble products on the pipe wall.

Unpublished information and firsthand observations have shown that crustation may exist simultaneously or separately in a specific pipeline. Also, tuberculation and afterprecipitation may exist together or separately. This study is concerned almost exclusively with incrustation, primarily with

the tuberculation resulting from corrosion. Methods for control of after-precipitation of insoluble products are generally well established, although not necessarily applied.

The first major problem which confronted the present investigation was that of evaluating and developing "tools" or criteria for measurement not only in laboratory and field studies of corrosion and tuberculation, but also

alone, without a head loss measurement, and interprets it in terms of flow capacity (a high factor indicates good capacity, and a low factor poor capacity). The head loss and velocity data, as well as accurate velocity factor data, can be indirectly related to roughness. An important consideration for this study is evaluating the extent to which capacity determinations will indicate the physical thickness of roughness and

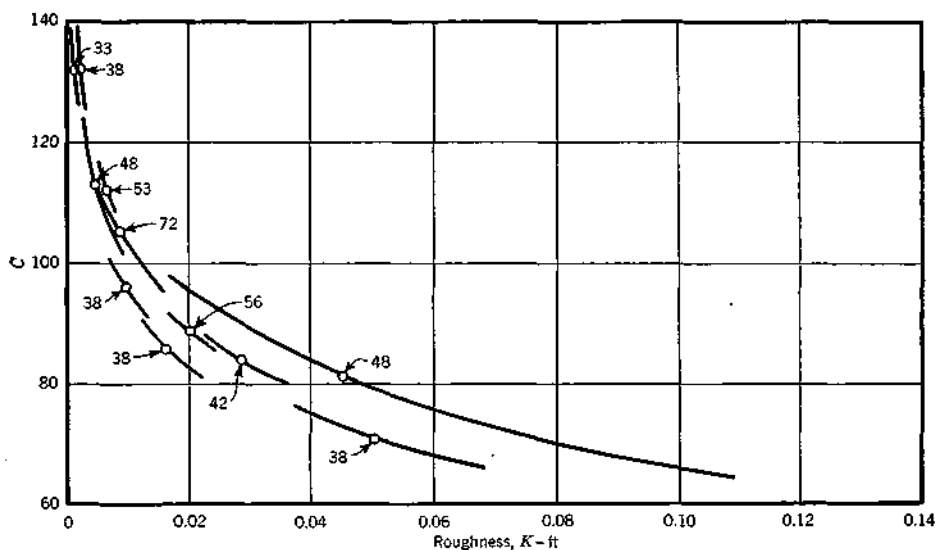


Fig. 1. Relation of Head Loss Accuracy to Roughness Calculation

The figures on the curves indicate the age of pipes in years. Thus, for a 48-yr-old, 30-in. pipe with a 1.20-ft head loss in 2,810 ft at a velocity of 1.2 fps, C is 81 and K is 0.045 ft. For the same pipe, at 1.70-ft head loss, C is 65 and K is 0.11 ft. At 0.70-ft head loss, C is 96, K is 0.017 ft.

in the study of pipe roughness resulting from tuberculation and other causes.

Measurement of Roughness

Current methods of determining flow capacity usually involve measuring the velocity and head loss. Another procedure accurately determines the velocity factor (average velocity divided by the velocity at center)

be comparable for different pipe diameters.

The velocity of flow through a pipe under a measured head loss can be accurately determined within the limits of observational error, specifically at the conditions of the test. A "capacity coefficient," such as the well known Hazen-Williams C, can be calculated to depict the carrying capacity for pipe of the same size under similar condi-

tions. The coefficient, however, is not a direct indication of roughness. The same measured data can also be substituted in the Darcy equation for the friction factor (f) and then in the lesser known Colebrook-White equa-

and K is the effective height of roughness, equivalent to sand grains of diameter K expressed by the above equation.

The relationship expressed by the above equation is considered basic in

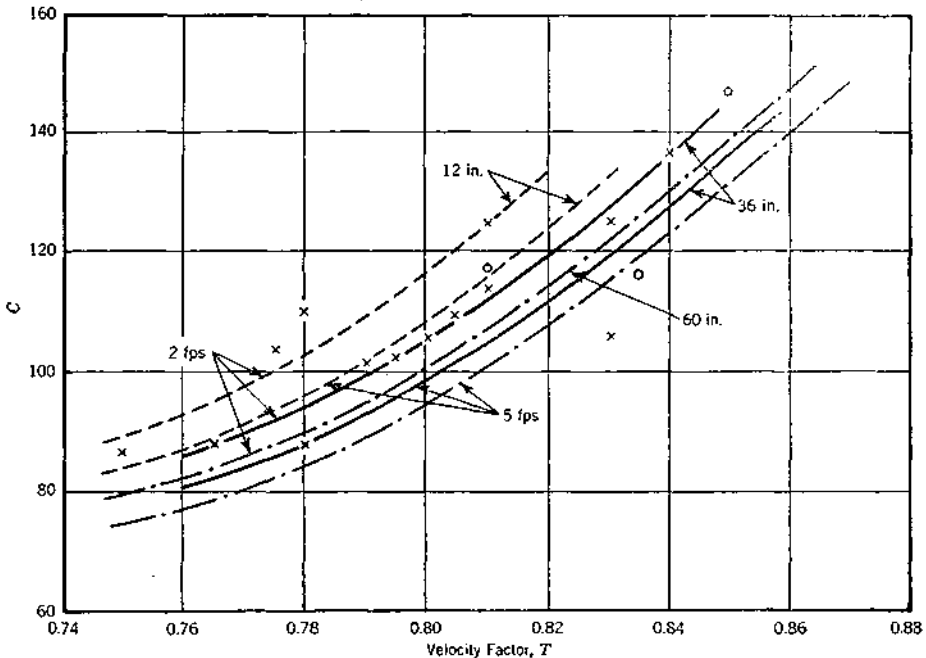


Fig. 2. Correlation of Velocity Factor and Hazen-Williams C

The velocity factor coefficient is the ratio of average velocity to maximum velocity at the center. The symbol X indicates coated cast iron pipe; the symbol O, concrete. All points represent data from reported field tests on 36-in. pipe. Ranges indicated for all pipe are empirical.

tion (l) to provide a calculated or "effective" roughness height (K), or a "roughness coefficient":

$$\frac{1}{\sqrt{f}} = 1.74 - 2 \log \left(\frac{18.7}{R\sqrt{f}} \right) + \frac{K}{r}$$

in which f is the friction factor; R is the Reynolds number; r is the radius;

modern fluid mechanics and has been stressed rather strongly at recent meetings of the International Water Supply Congress (2, 3). The roughness coefficient is comparable for similar roughness in pipes of different sizes and should serve as a possible comparable unit for measurement of incrustation.

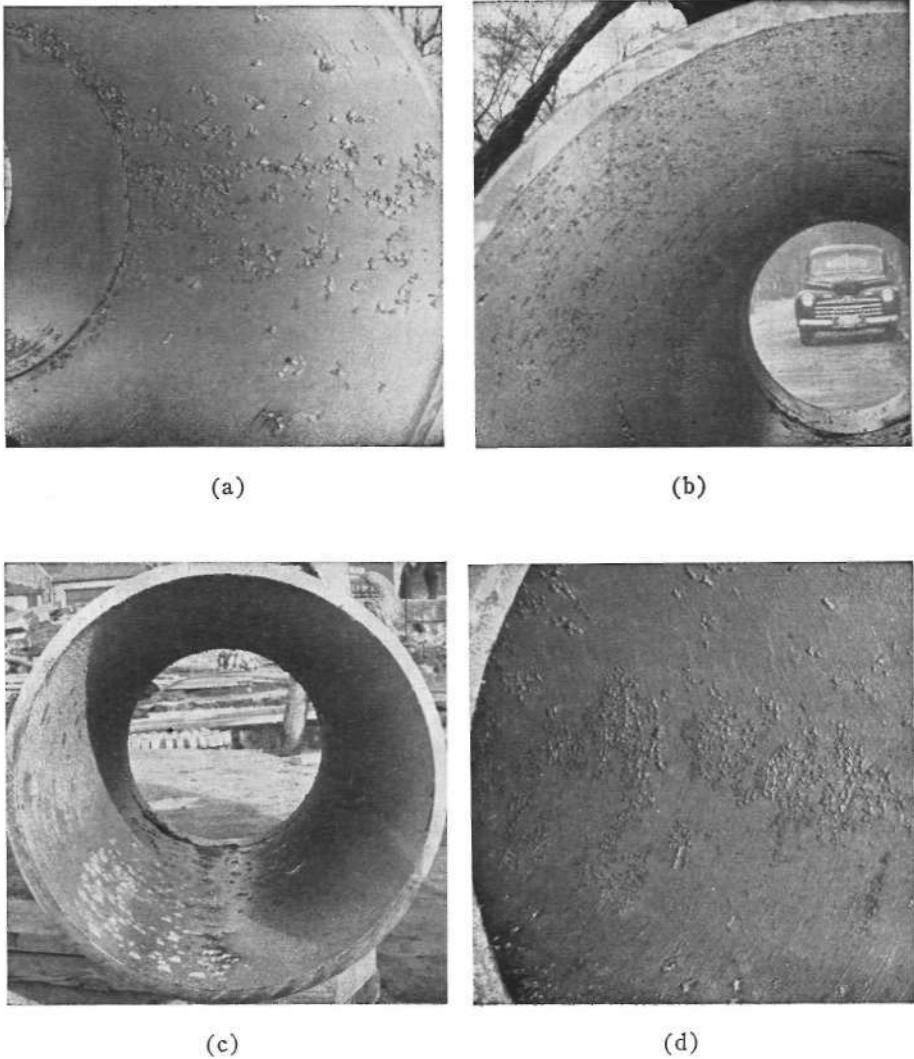


Fig. 3. Conditions of Tuberculation and Afterprecipitation

These deposits resulted from 21 months of operation by coagulation and settling. The velocity factors are as follows: (a) 48-in. diameter, average $T = 0.803$ ($C = 102 \pm$), $K = 0.0100$ ft; (b) 48-in. diameter, average $T = 0.785$ ($C = 94 \pm$), $K = 0.0180$ ft; (c) 24-in. diameter, average $T = 0.754$ ($C = 84 \pm$), $K = 0.0240$ ft; (d) 48-in. diameter, average $T = 0.755$ ($C = 81 \pm$), $K = 0.0480$ ft. All pipes were removed from within $\frac{1}{4}$ mile of traverse location.

For a comparable calculated or effective roughness of 0.03 ft, C (Hazen-Williams) would be 74 for a 12-in. pipe and 86 for a 48-in. pipe. For a comparable C of 86, K would be 0.015 ft in a 12-in. pipe and 0.03 ft in a 48-in. pipe. Similar comparisons can be made for smooth pipe. Thus, for an equivalent C , the depth of roughness in a 48-in. pipe is calculated to be approximately twice that in a 12-in. pipe.

Accuracy

In the determination of C , it is frequently reported that the accuracy of the head loss determination is ± 0.5 ft. Thus, for example, a ± 10 per cent accuracy in head loss represents an approximate error in C of 5 per cent for a 36-in. pipe at 3 fps, corresponding to the following:

C	
130	(from 123.5 to 136.5)
80	(from 76 to 84)
K (ft)	
0.0014	(from 0.0008 to 0.0021)
0.0380	(from 0.030 to 0.052)

In a randomly selected series of tests at one municipality, such error could amount to as much as 2-20 per cent of C for the eleven mains involved. It will be noted in Fig. 1 that the absolute error is large for C and low for K in clean pipes. In rough pipes, however, a small error in head loss corresponds to a large error in the roughness calculation. Other variables of more or less significant proportion lie in the measurement of velocity (± 1 per cent of C), the neglect of viscosity (± 2 per cent of C , from 60°F), and the sometimes unknown loss of water (takeoffs) between the points of measurement of head loss.

Velocity Factor

The other procedure used for estimating the carrying capacity and the roughness consists of a careful measurement of the velocity factor. Although this is an approximate determination, it correlates surprisingly well with the Hazen-Williams C . Figure 2, based on carefully determined velocity traverses, shows this correlation. The degree of care exercised in the determination of this parameter affects its validity. Obviously the velocity traverse is not valid if it is not symmetrical about the centerline. To insure symmetry, the traverse must be made on a long, straight section of pipe under steady flow conditions. Preferably, a second velocity traverse should be made at a 90-deg angle from the first. Precaution should also be taken to insure that all primary readings are made at a specific velocity. The usefulness of this parameter, of course, requires that the section of pipe upstream (which has been responsible for the velocity pattern) is representative of the type and quantity of roughness throughout the entire pipe under test. That this is not always true is shown in Fig. 3C.

With refinement in technique and in mathematical analysis this method may prove to be more valuable for calculating pipe roughness. It is beyond the scope of the present study to pursue this question further, however.

The most serious criticism of the C value of Hazen-Williams, the K of Colebrook, and the pipe traverse procedure, lies in the fact that even if they are highly accurate, they do not distinguish between the types of roughness, such as tuberculation and afterprecipitation, or sedimentation and slime.

The series of photographs in Fig. 3 represents conditions of tuberculation and afterprecipitation in mains having velocity factors of 0.803-0.754. These pipes all show a rippled deposit of silica and alumina as well as tuberculation. The deposit resulted from 21

data on velocity factor. This type of data was the only data available in a substantial quantity, and the relative roughness height was calculated from the empirical relationship shown in Fig. 2. It can be interpreted only to mean that a change took place after

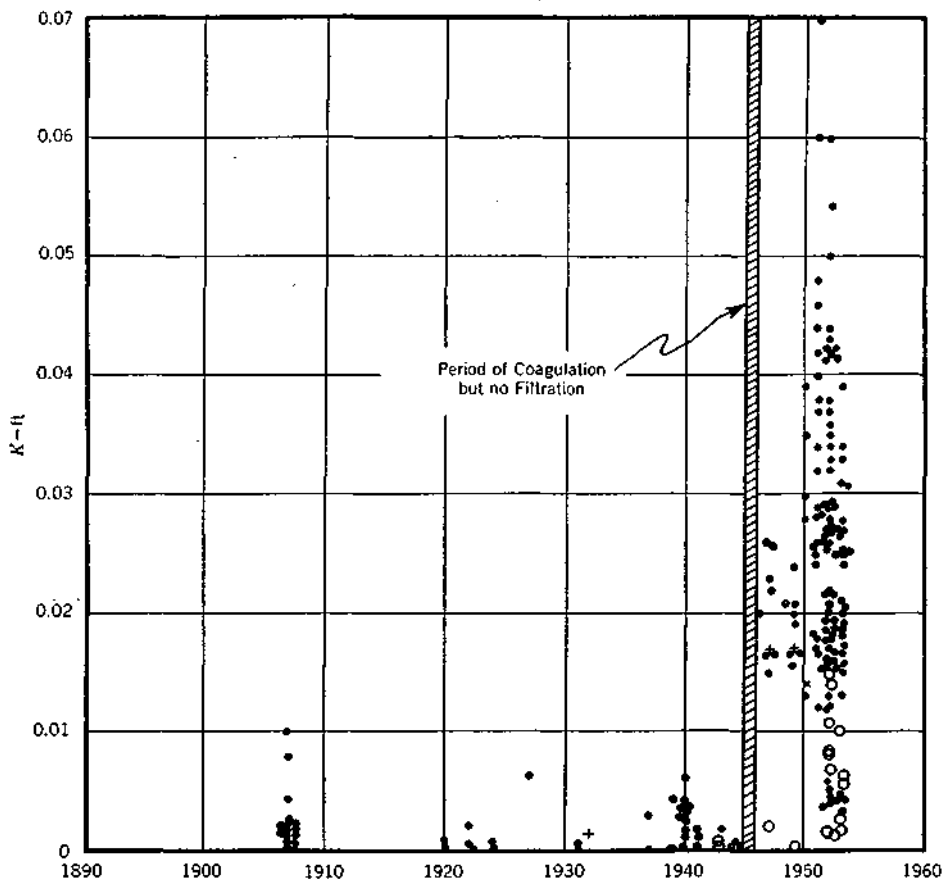


Fig. 4. Calculations of Roughness Height

These roughness determinations were calculated from velocity factor T.

months of operation by coagulation and settling, but without filtration. Two other locations have provided data indicating no pipe with K greater than 0.01 ft, using untreated Great Lakes water.

Figure 4 represents calculations of roughness heights determined from

the treatment plant was installed. Fig. 4 is associated with the photographs in Fig. 3.

From the preceding figures and discussion it appears improbable that a precise understanding of the type or quantity of roughness can be obtained from the capacity tests in present use.

They are not designed specifically to indicate such small degrees of tuberculation as might have developed during a relatively short period of change in chemical treatment. Very low values of C , as usually determined, indicate only roughness of major proportions. There is, therefore, no completely satisfactory criterion for the physical condition of the pipe interior. This is not a criticism of flow tests when carefully made to determine carrying capacity, however, but an evaluation to indicate a limitation on the extent to which such tests can be used, even comparatively, to determine a change in pipe roughness, specifically tuberculation.

Tuberculation

Because tuberculation results from corrosion, the problem demands that a field "tool" be developed to indicate the corrosive potential of water—not to determine roughness, but to determine corrosivity as distinct from sediment or deposition. This tool must be usable at any place in the distribution system and under any condition of flow. It must be sensitive to the effect of supersaturation with calcium carbonate as a corrosion inhibitor (not as an incrustant) and to other inhibitors that may be present. It must also be sensitive to the effect of the possible corrosives which may be present, such as dissolved oxygen, or low pH.

The development of such an indicator would help to solve the current problem, and it is toward this objective that much of the laboratory testing is being directed. At present, a method involving measurement of potential changes induced by applied current densities of a few microamperes per square decimeter seems to offer the best hope. Results from this method show increasing promise, but they are

not sufficiently conclusive to warrant detailed discussion at this time. It is possible, too, that the method may have limited application.

It has been frequently—almost persistently—suggested that experimental pipelines be tested at one or more water plants and observed with treated waters of various chemical qualities. The objective of this procedure has merit, but cost and time are practical considerations that cannot be overlooked, particularly when it is realized that literally dozens of modifications in treatment would require evaluation. It is estimated that, if five parallel lines of 4–8-in. pipe were installed for this purpose, the cost of appropriate valves, orifices, and chemical-feeding equipment would be more than \$10,000, even if a constant-head supply of 0.5 mgd were available. Furthermore, such tests may require months or years to assure reliability of observations unless a satisfactory tool is developed.

Field Studies

Field visits to a number of plants have disclosed several significant differences in the quality of treated water. In general, one group provides water of pH 7.3–7.5 and another group, pH 7.9–8.2. The former makes no attempt to maintain calcium carbonate saturation. Some plants in the second group maintain a relatively constant pH with no regard to the temperature effect on CaCO_3 solubility. If this means of stability is to be used, it should be recognized that the saturation pH (as determined at the temperature of the effluent) varies from about 7.95 at 77°F to 8.45 at 32°F.

As for effluents of pH 7.3–7.5, oral reports indicate little or no loss in carrying capacity in some cases, but this was without flow test data. One plant reports severe losses in many

mains, as indicated in part by flow tests. In this case, however, the data are complicated by the known presence of afterprecipitation and old silt depositions prior to coagulation and filtration. Examination of pipes revealed frequent tuberculation.

Another plant frequently produced an effluent of pH 6.8-7.0. Flow tests indicated a C coefficient of 93 (K

precluded field evaluation of this factor.

Wide variations in sampling and analytical procedures preclude any evaluation of silica and alumina residuals in the treated effluents. Further study of the solubility of alumina and silica at various temperatures, as influenced by pH and other mineral variations, would be valuable.

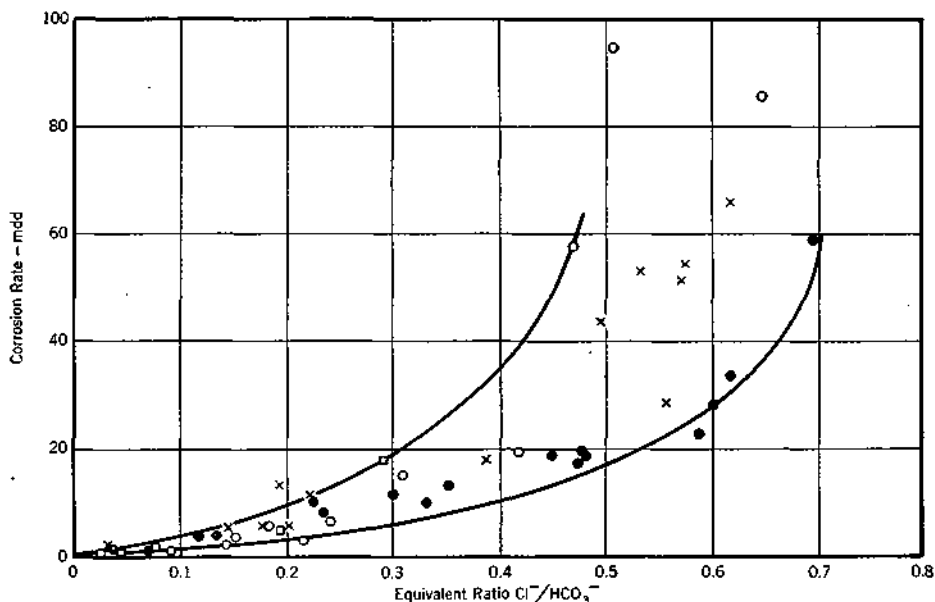


Fig. 5. Effect of Cl^-/HCO_3^- Ratio on Corrosion of Mild Steel

Alkalinity (as $CaCO_3$) is shown as follows:

— 75-100 ppm.

○—150-180 ppm,

X—120-135 ppm,

—250-260 ppm.

The abbreviation "mdd" stands for milligrams per square decimeter per day.

— 0.013 ft) in a new 24-in. main from the plant after 4 years of use.

Several plants used marginal chlorination (less than 0.1 ppm NH_2Cl); one used chlorine dioxide; one carried free and combined chlorine; and another had carried free chlorine for a period of about 8 years. Other alterations in treatment during this period and the insensitivity of flow test data

Samples of incrustation received from several plants are being analyzed to determine their compositions.

Laboratory Studies

Jar tests are being conducted in the manner described by Larson and King (4) using steel and cast-iron specimens.

After considerable time had been spent in evaluating various methods of preparing specimens, it was found that very minor stresses imposed on the steel by lack of care in handling promoted excessive variability in results. Subsequent testing accompanied by potential measurements established a corrosive-inhibitive relationship for various equivalent ratios of chloride-

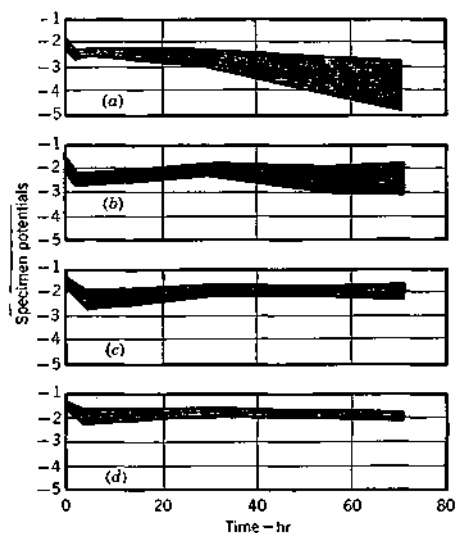


Fig. 6. Potential-Time Data at Four Levels of $\text{Cl}^-/\text{HCO}_3^-$.

Increasingly high rates of corrosion occur as the chloride-bicarbonate ratio increases. Range of $\text{Cl}^-/\text{HCO}_3^-$ ratio: (a) 0.57-0.63; (b) 0.29-0.36; (c) 0.18-0.21; (d) 0.06-0.10. Specimen potentials are in volts versus saturated calomel electrode.

bicarbonate salts of sodium at pH 7, as shown in Fig. 5.

This figure would appear to indicate that even small proportions of chloride to alkalinity cause some corrosion. Potential-time data show, however, that under these conditions corrosion appears to be somewhat high on initial immersion but becomes at least partially

inhibited with time. The potential-time data at four levels of $\text{Cl}^-/\text{HCO}_3^-$ are shown in Fig. 6. This is a qualitative, not a quantitative, measure of corrosion rates. From these data it appears that increasingly high rates of corrosion occur as the chloride to bicarbonate ratio increases, particularly above a value of 0.3. This proportion approximates the proportion of chloride plus sulfate to bicarbonate in Great Lakes waters and classifies (4) such water in a range which is sensitive to additional corrosives and probably inhibitors.

C. H. Spaulding, in a preliminary unpublished study of this problem, suggested that free chlorine appeared to

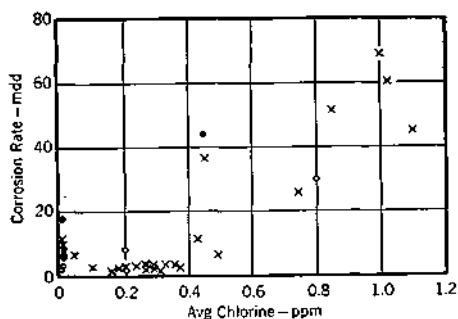


Fig. 7. Effect of Free Chlorine on Corrosion of Mild Steel

The alkalinity (as CaCO_3) was 120-135 ppm. The chloride-bicarbonate ratio was 0.18-0.27. The running time of the test is indicated by X = 3-4 days, O = 10-20 days. The pH was 7 in all cases except where = indicates a pH of 8.

be responsible for excessive tuberculation. This and other work on the problem (5) prompted the undertaking of a number of tests to obtain a relative evaluation of this factor. These tests indicate (Fig. 7) that free chlorine in concentrations above 0.4 ppm corrodes steel at room temperature in aerated water of about 120 ppm

alkalinity and 30 ppm sodium chloride, pH 7 and 8, at low velocities. In Fig. 8, these results have been superimposed on the previous Fig. 5 to indicate the relative corrosion rates at the particular chloride-bicarbonate ratio. Figure 8 also shows the results of tests of 3-6 days' duration using chloramine in concentrations of 0.4-3.6 ppm. These data appear to indicate that corrosion is somewhat inhibited by this means.

rather than 30 ppm, the additional corrosion induced by 0.4-1.0 ppm chlorine may have been negligible. No additional studies have been made on other corrosives or inhibitors.

Tests have also indicated corrosion rates to be higher at pH 8.5 and 9.0 than at 7.0, 7.5, and 8.0. A twofold increase in corrosion rate resulted when the velocity was increased from 0.14 to 0.89 fps at pH 8.5 and 9.0 with

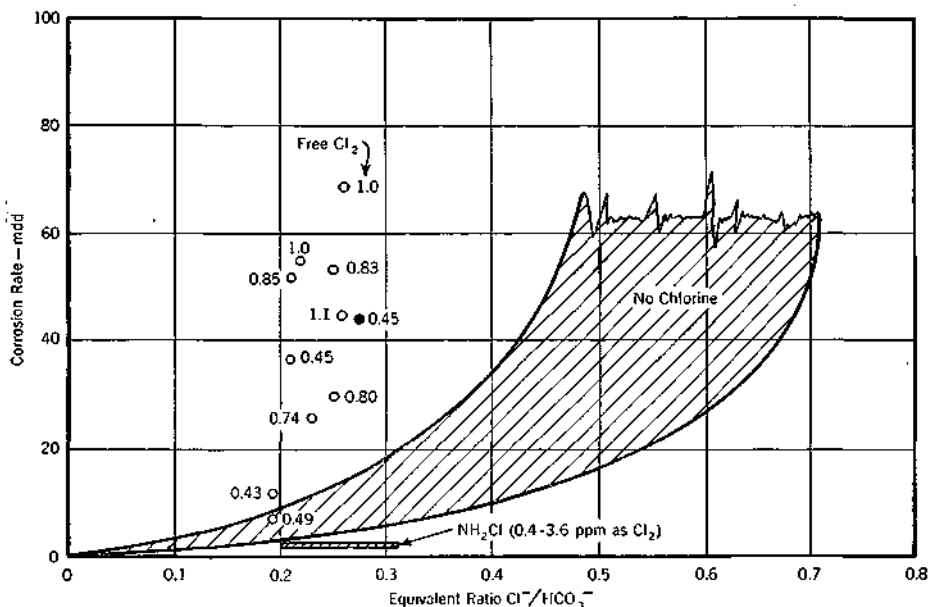


Fig. 8. Relative Corrosion Rates at Particular Chloride-Bicarbonate Ratios.

Effects of free chlorine as shown in Fig. 7 have been superimposed on Fig. 5 to show the relative corrosion rates.

It is probable that similar relative results would *not* have been obtained at other proportions of chloride to bicarbonate. If 5 ppm sodium chloride had been used rather than 30 ppm, a greater proportion of inhibitor would have been present and more than 0.4 ppm chlorine may have been necessary for comparable corrosion rates. If 80 ppm sodium chloride had been used

1,000 ppm alkalinity and 120 ppm sodium chloride. This is shown in Fig. 9. Minimum corrosion was noted at pH 7.0, 7.5, and 8.0 at both rates. As high pH is normally considered an inhibitor, the data on this character of water are reported to indicate what may be considered as lack of a basic standard of corrosivity. It is only from basic information on the correla-

tive influence of the primary corrosive ion (Cl^-) and inhibitive ion (HCO_3^-) that reasonable and consistent progress can be made. These jar tests are somewhat crude, but the general trends of the influence of variables are certain. The border line influence of minor variations of these and other variables will require even more accurate techniques than are now available. As mentioned previously, efforts are being made to develop the necessary tool for this purpose.

Coatings

The desirability of coatings is obvious. Without them, in an aggressive water, corrosion and tuberculation would occur even more seriously. It is reasonable to believe that less inhibitor will be required to protect a coated pipe than an uncoated pipe, just as in cathodic protection less current is required for coated surfaces than for uncoated surfaces. Limiting the problem to the usual coal-tar type of internal coating, very little has been published on its application or composition. No specifications for cast-iron pipe coal-tar coatings are in effect, for reasons beyond the scope of this discussion.

It is of course the aim of every manufacturer to produce a passable coating that will meet competition. As is true for any item manufactured without suitable standards or specifications, differences should be expected to exist even in the coating of a single producer. It is therefore not surprising to note that in a single shipment of pipe some will show the effects of weathering, while others will not. There will be flaws in some and not in others. Some will resist an aggressive water over a period of years, some will not.

There is no coating, lining, plating, or paint job that is absolutely infallible, but it is probable that both sprayed and dipped coatings can be improved by standardization. The producers of tar coatings and the pipe manufacturers might also evaluate the possibility of impregnating the coating with an appropriate inhibitor for the benefit of the industry. Again, the extent of the

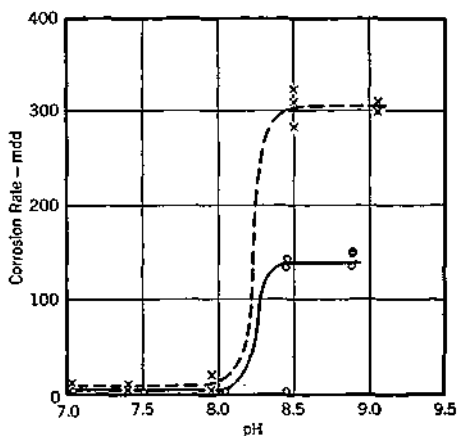


Fig. 9. Effect on Corrosion Rates of Increased pH and Change in Velocity

At pH 8.5 and 9.0, the 0.14-0.89-fps increase in velocity doubles the corrosion rate. In these tests, conditions were as follows: X indicates a velocity of 0.89 fps, a chloride-bicarbonate ratio of 0.16, and an alkalinity of 700; O indicates a velocity of 0.14 fps, a chloride-bicarbonate ratio of 0.10, and an alkalinity of 1,050.

effectiveness of such an inhibitor will depend on the degree of aggressiveness of the water as well as the overall quality of the coating.

Summary

A bibliography has been prepared on the subject of carrying capacity. It covers approximately 160 papers by about 260 authors.

Study of loss in carrying capacity is being limited to tar-coated cast-iron mains, specifically those in the Great Lakes region. Primary, but not sole, concern of the investigation is the losses due to tuberculation.

The head loss-velocity test for capacity has been evaluated and found inadequate for use as a critical indicator of roughness, specifically by tuberculation. It does not distinguish between various types of roughness. There is need, therefore, for the development of a laboratory and field tool for the measurement of corrosivity. This is a basic preliminary objective of this study.

Field visits have been made to examine pipe, to obtain flow test data, chemical analyses, treatment data, and the views of persons in close contact with the problem. In 10 months over 500 specimens have been used in approximately 45 series of tests during which about 9,000 operations such as cleaning, weighing, and quality control testing, have been carried out. Over 16,000 current and voltage readings have accompanied these tests.

Through careful laboratory tests, free chlorine has been found to be corrosive to steel at concentrations above 0.4 ppm, at low velocity, at room temperature, in water of 30 ppm NaCl and 120 ppm alkalinity at pH 7. Under these conditions chloramine in concentrations up to 3.6 ppm was not found to be significantly corrosive.

Tar coatings are desirable and may be improved.

Acknowledgments

This survey is supported by Research Grant G4007(R) from the Na-

tional Institutes of Health, US Public Health Service. Because adequate personnel have not been available, only about half of the first-year funds has been spent. A 6-month extension has been requested and received without prejudice to subsequent appropriations. Substantial support is also derived from the Illinois State Water Survey.

Grateful acknowledgment is also made to the many water works personnel who have cooperated wholeheartedly toward the preparation of this preliminary and summary report. The many helpful discussions with members of the AWWA advisory committee and others have been highly valuable in orienting and outlining the existing problem.

Particular acknowledgement is due A. M. Buswell, whose active interest as chairman of the AWWA advisory committee and as supervisor of Research Grant G4007(R) contributed invaluable guidance.

References

1. COLEBROOK, C. F. & WHITE, C. M. The Reduction of Carrying Capacity of Pipe With Age. */. Inst. Civ. Engrs. (Br.)*, 7:99 (1937).
2. LAMONT, P. A. The Reduction With Age of the Carrying Capacity of Pipelines. *j. Inst. Wtr. Engrs. (Br.)*, 8:53 (1954).
3. LAMONT, P. A. A Review of Pipe Friction Data and Formulae With a Proposed Set of Exponential Formulae Based on the Theory of Roughness. *Proc. Inst. of Civ. Engrs.*, p. 248 (1948).
4. LARSON, T. E. & KING, R. M. Corrosion by Water at Low Flow Velocity. *Jour. AWWA*, 46:1 (Jan. 1954).
5. WILLIAMS, D. B. Dechlorination Linked to Corrosion in Water Distribution Systems. *Wtr. & Sew. Wks.*, 100:3 (Mar. 1953).